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ABSTRACT

Corrosion of rebar in concrete bridges causes subsurface cracks and is a major cause of structural degradation that necessitates repair or replacement. Early detection of corrosion effects can limit the location and extent of necessary repairs, while providing long-term information about the infrastructure status. Most current detection methods, however, are destructive of the road surface and require closing or restricting traffic while the tests are performed. A ground-penetrating radar imaging system has been designed and developed that will perform the nondestructive evaluation of road-bed cracking at traffic speeds; *i.e.*, without the need to restrict traffic flow. The first-generation system (called the HERMES bridge inspector), consists of an offset-linear array of 64 impulse radar transceivers and associated electronics housed in a trailer. Computers in the trailer and in the towing vehicle control the data acquisition, processing, and display. Cross-road resolution is three centimeters at up to 30 cm in depth, while down-road resolution depends on speed; 3 cm below 20 mph up to 8 cm at 50 mph. A two-meter-wide path is inspected on each pass over the roadway. In this paper, we describe the design of this system, show preliminary results, and lay out its deployment schedule.

Keywords: ground-penetrating radar, bridge inspection, nondestructive evaluation, concrete delamination, rebar corrosion, diffraction tomography, road-bed imaging, impulse radar, synthetic aperture radar imaging

1. INTRODUCTION

In previous studies [1], we have determined parameters needed for an advanced ground-penetrating radar system that could scan concrete and asphalt road-beds for evidence of corrosion damage and evaluation of the rebar mesh. The unique requirements of this radar are its relatively high cross-range resolution (3 cm), wide frequency bandwidth (1 to 5 GHz), and relatively low cost to allow the development of an array. Concurrent development of the so-called Micropower Impulse Radar [2] at the Lawrence Livermore National Laboratory (LLNL) has made this type of radar inspection system possible. Its small size, low power, and low cost have made MIR appropriate for many short-range motion sensing and ranging applications. More recent studies confirmed that synthetic aperture MIR arrays can penetrate (dry) concrete slabs to 30 cm and achieve the desired imaging resolution.

In Winter 1995, the Federal Highways Administration (FHWA) initiated a project with LLNL to build a first such prototype imaging system as a demonstration of its capabilities. The primary objective of this project is to provide a new tool and set of analysis techniques for inspection of concrete bridges and roads. This tool, called the HERMES bridge inspector, is also expected to perform the inspection fast enough so that the vehicle carrying the array does not impede traffic or cause a lane closure. Destructive methods of inspection, such as coring, are costly not only because of the effort required to obtain a core sample but also because of the large costs of traffic diversion. By employing a rapid and totally nondestructive evaluation methodology, HERMES could result in a more cost-effective and timely means of bridge-deck inspection.

In this paper, we describe the work-in-progress on the HERMES bridge inspector system. The complete radar, antennas, computer and power supply are housed in a 30-foot long trailer that can be towed by a standard one-ton truck (Figure 1). It is currently in the final stages of assembly and is scheduled for full scale testing in early 1997. We will describe the overall system design and the major hardware components. We will also layout the general data flow and the processing steps from the raw radar returns to imaging of flaws. Finally, the plans for testing and deployment of the full system will be presented.

Fig. 1. Photograph of the HERMES bridge inspector trailer. The complete radar imaging system, with power supply and computer for data analysis, is housed inside.

2. SYSTEM REQUIREMENTS

The first phase of the HERMES project involved an extensive specification of system requirements through modeling, experimentation, and analysis. This process also determined the performance measures that will be used to verify the final system performance. In this section, we describe the requirements specified for the HERMES bridge inspector and what processes took place in their selection.

2.1. Bridge-deck inspection parameters

For structural engineers, the most important features to be detected in concrete bridges are the horizontal (flat) delaminations of concrete layers due to residual corrosion effects in the rebar layers. These delaminations or cracks are either air- or water-filled. The desired inspection performance level is to detect delaminations of down to one-millimeter (40 mil) thickness and greater that 10 cm in extent. This specification, along with knowledge of the materials involved, allow modeling of the radar cross section (RCS) of these cracks and hence the acceptable signal-to-noise tolerances for detection.

The other major features to image are the rebars themselves. From experimental analysis we can see that, while rebar is smaller than three centimeters in diameter, the contrast is such that spatial resolution of 3 cm gives sufficient discrimination to locate the rebar. (Also, the long dimension of the rebar increases its RCS and enhances detection.) At that resolution, it is impossible to detect corroded (versus uncorroded) rebars. Instead, this is why we study the *products* of corrosion that cause the secondary cracking and delamination. In any event, analyses of crack and rebar RCS allow us to generate detection models in various noise and clutter environments. Coupled with baseline radar data in concrete, these models help to specify the radar system parameters. To date, all tests have been conducted with single-element (one transmit, one receive) radar systems.

Determination of radar specifications required extensive combined use of modeling and experiments. The approach was to start with electromagnetic (EM) measurements of the basic MIR rangefinder and generate a validated model of its operation. Modifications were proposed, modeled, simulated, and made into prototypes. These prototypes underwent testing to verify that the performance matched expected values. At the same time, swept-frequency tests were performed on various concrete and asphalt surfaces to determine dielectric and attenuation properties of those materials. Several concrete slabs, with and without asphalt covering, were fabricated and employed in detailed testing of radar inspection. We used various radar and antenna configurations to evaluate the performance in the field. In this section we describe one such scan and show the imaging results with associated analyses. This type of analysis will also be used in a battery of tests planned for the final HERMES system.

2.2. Example inspection study

We performed a swept frequency analysis of one particular concrete slab prepared by the FHWA that contains known flaws measured acoustically. Our tests consisted of first scanning the slab using a swept frequency radar system, which provides an accurate and controlled wideband response from scattering within the slabs. These tests provide fundamental bandwidth and radar cross section information that is not attainable using the other impulse radars or the baseline MIR. We used this information to optimize the MIR for the FHWA bridge deck inspection system. Other information provided by these tests was critical for determining and verifying final array design parameters such as array coupling, array element size and spacing, and array height above the surface of the concrete.

The concrete slab was known to contain several delaminations that are representative of those found on "real" bridge decks. Information as to the nature or location of delamination within the slab was withheld until the images were processed. The slab is 120 cm by 150 cm (4 feet by 5 feet) and 23 cm thick. It had aged for a considerable length of time and therefore is assumed to be completely cured. At the time of testing the slab was outdoors, however it was covered with plastic to keep it dry. We were asked to scan and analyze the slab using our radar and processing equipment. The following is our analysis, which closely matched the FHWA analysis acquired through other methods.

After the swept-frequency tests, the entire slab was scanned with a single MIR unit using a mobile robotic scanning device. Spatial sampling was 1 cm and a total of 167x172 scans were acquired with 512 samples per scan. Figure 2 shows the reconstructed planar slices at various depths within the slab, and it is in these slice images, rather than a 3D rendering, that we see a detailed visualization of the interior of the slab. There are two large square metal objects in the slab placed there for diagnostic reasons. Other diagnostic devices such as the wires buried just beneath the surface of the slab were undetected by the radar (being smaller than the resolution cells) and are not apparent in any of the images. The first sign of delamination between rebars occurs at about 4 cm down in the center of the image. The depth of the delamination comes into view clearly at 6 cm and fills the region between the two rebars, which are separated by approximately 32 cm. The delamination appears to be approximately 30 cm square. The back surface of the slab was detected by the radar and was visible in deeper depth planes of the image (not shown in the figure).

Vertical rebar in the slab (i.e., those rebar that look like vertical lines in the images; they are all, of course, horizontal in the slab) appear at regular intervals of approximately 32 cm. All appear to be at approximately 6 cm depth except for the rebar at the far right, which appears to be at about 5 cm. The rebar directly to the right of the delamination appears to be disconnected in the image, which could indicate rebar corrosion. The radar was vertically polarized giving preference to the vertical rebars and therefore the horizontal rebars are difficult to visualize. The polarization not only affects visualization of polarization dependent targets, but also affects the cross coupling between array elements in the antenna array design. As noted below, we are using 45-degree polarization in the final system to provide a more balanced visualization of horizontal and vertical rebars.

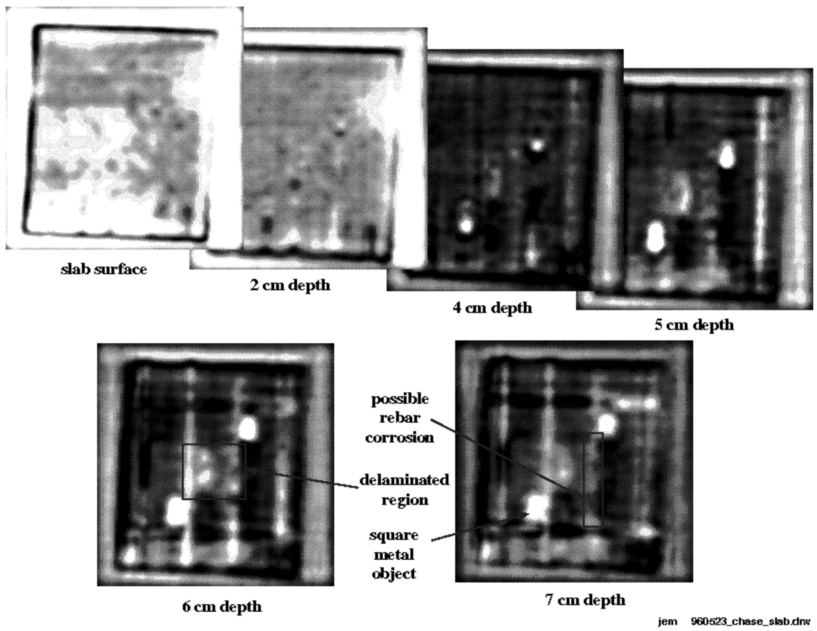

Fig 2. Reconstructed images of a concrete slab at various depths (see text for details).

2.3. Specifications

Table 1 below lists some of the major design specifications that resulted from the detailed analysis work in the previous sections. These specifications drove the final HERMES design.

Table 1. HERMES design parameters and their specifications.

Parameter	*Value*
Cross-road and down-road resolution	3 cm
Desired range resolution (into concrete)	3 cm
Desired speed of travel	Variable, up to 50 mph
Pulse Repetition Frequency (PRF)	5 MHz
Sweep Frequency	up to 20 KHz
Radar bandwidth (3dB)	0.5 to 5 GHz
Dynamic range (12-bits required for imaging)	90 db
Averaging	1 (no averaging)
Height above road surface	more than 10 cm
Antenna beamwidth	90 degrees

3. THE HERMES DESIGN

In this section, we describe the design characteristics of the HERMES bridge inspector based on the system requirements above. This is not meant to be a complete specifications document, but simply to provide an overview of the system design. As with other prototype engineering projects, the final design represents a series of trade-offs in cost, schedule, and performance. The seven subsystems of HERMES subsystems (antennas, array, radar, interface electronics, computer, data processing, and vehicle) are shown in the architectural block diagram of the HERMES system in Figure 3. We will describe each in more detail in the subsections below.

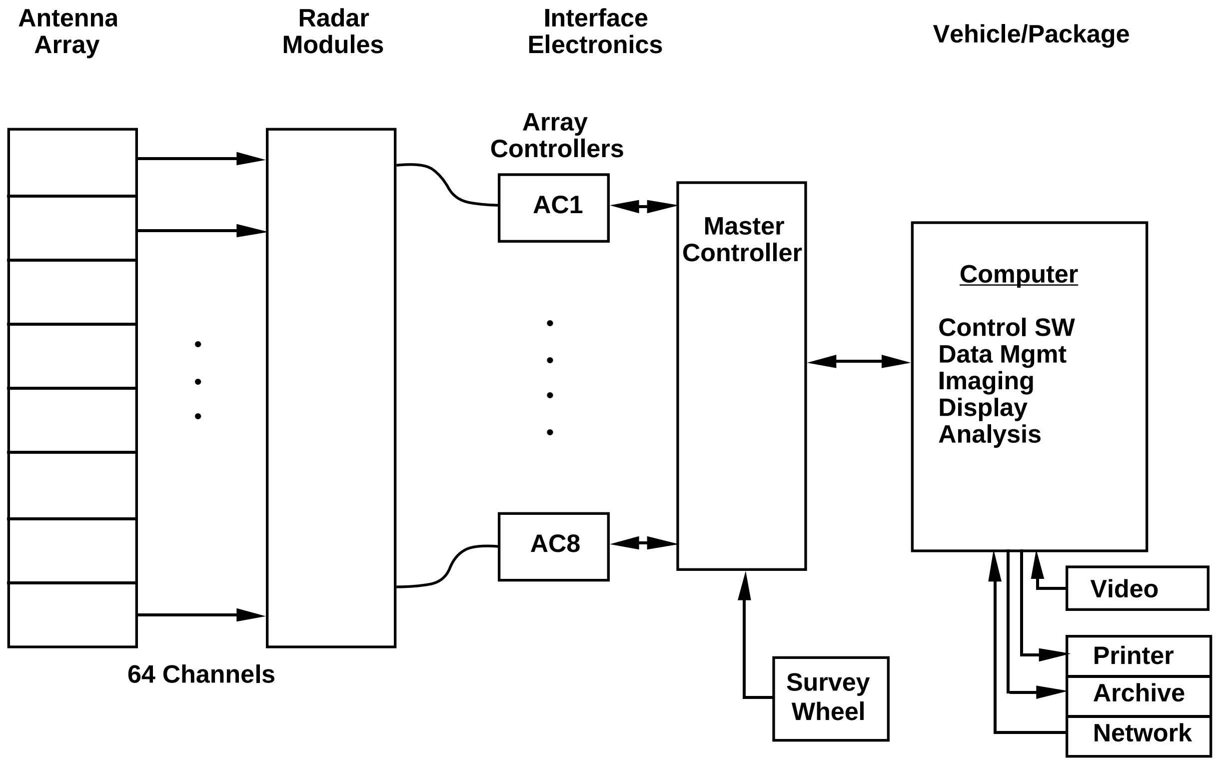

Fig. 3. Block diagram of the major subsystem components of the HERMES bridge inspector.

3.1. Antennas

A scaleable ultra-wideband ridged-horn antenna with good pulse characteristics and beamwidth for imaging has been developed. The antenna design was a challenging engineering task because it had to meet the specifications above as well as be easily manufactured. For the 64 transmit and receive elements needed to meet the resolution specifications, 128 antennas have been fabricated at low cost. The design has a flat bandwidth (.5 to 5 GHz), good impedance characteristics (50±15 ohm), a 90-degree beamwidth for imaging. In addition, the horn and ridges are made of etched brass that can be quickly folded and soldered. Measurements of the radiating characteristics match the simulated values very closely. The horn opening for each antenna is 5.5 by 7.5 cm. Transmit and receive antennas are separated by 2.5 cm to maintain close proximity, but reduce the saturating effect of the direct coupling pulse.

3.2. Antenna Array

Design for the full array of antennas and its mounting structure was driven by the conflicting needs to achieve good spatial resolution while minimizing coupling interactions between transceiver elements. Antenna coupling refers to multiple bounces between the road surface and the reflecting surfaces of the array antennas. By keeping the elements distant from one another and filling empty spaces with radar-absorbing material, the coupling noise is reduced significantly. Through simulations [3] we have determined the worst-case clutter due to the combined coupling from all the surrounding antennas during a single scan is the parameter of interest. We have designed the array so that at the 10-cm height above the road surface the combined coupling pulse is 16 db below the expected rebar return signal; this should be an acceptable figure.

A linear array of radar elements that spans the road-way at 3-cm spacing is the desired configuration. However, with antennas much larger than the 3-cm desired resolution, it is impossible to place them side-by-side. Therefore, an offset linear configuration was chosen that allows 3-cm spacing along the direction of travel. Figure 4 shows a configuration of these antennas. A stiff mechanical fixturing in the vehicle allows the 2.1-by-2.1 meter array to be raised and lowered as required. For extremely slow-speed applications, the array can be lowered to street level. Environmental effects of temperature, vibration, stray radiation, etc. are all considered in the design. The transmit and receive antennas for each array element are co-polarized, and are both canted at a 45-degree angle relative to the motion of travel. This rotation is done to avoid preferential inspection of the rebar mesh in one direction; i.e., it allows inspection of rebar embedded both in the direction of travel and crosswise to it.

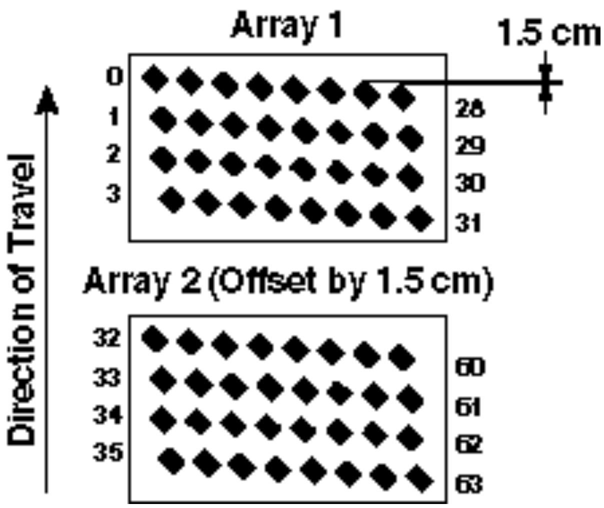

Fig. 4. Offset-linear array configuration for the HERMES radar antennas as viewed from the top. At left, each rectangle represents one pair of transmit/receive antennas rotated at 45 degrees so that both along-the-road and cross-road rebar orientations are detected. The array spatial sampling is 3 cm (cross-road) over a 1.9-meter width. At right, both sub-arrays are fabricated in one assembly.

3.3. Radar Subsystem

The basic MIR system was modified in several ways to accommodate the special requirements of HERMES. The main modification has to do with speed of operation. Due to the need for high-speed acquisition at 50 mph, we could not employ the multi-pulse averaging feature of MIR to reduce noise levels. Instead, each pulse is detected and digitized at each 200-ns sample time (5 MHz), so we used high-performance pulsers and amplifiers in the front end to achieve an overall dynamic range of 90 db. The usable bandwidth is from 500 MHz to 5 GHz with a 50-ohm impedance to match the wideband antennas. To reduce costs, eight receive antennas are multiplexed through one receiver module with little additional noise. These radar systems are still small enough to be completely enclosed and mounted on top of the array hardware for all 64 channels.

3.4. Interface Electronics

Two major components provide timing and control for the HERMES system—the master controller and the array controller. The master controller handles all the timing controls for each radar unit and serves as the main direct interface with the main computer. Synchronization of the radar data with other information (survey wheel and video) is all controlled by this subsystem. Communications with the computer take place over standard serial line (RS-232) and parallel port. The array controller decodes the address generated by the master controller for the particular transceiver of interest and causes it to initiate a scan. The master controller is physically housed in the rack containing the computer, while the array controller is mounted on the structure holding the radar array.

3.5. Computer

The main computer workstation (a dual-processor Sun UltraSparc 2 with 512 Mbyte of memory and a 2 Gbyte disk) is housed in the HERMES trailer and controls all aspects of data acquisition, processing, display, and analysis. For acquisition, the system has been tested out at 10Mbyte/sec sustained throughput to a separate 12-Gbyte RAID disk from the digitizing simulator. A parallel interface to the master controller receives the radar data synchronized to real-time video data from an external camera. Also attached are an archival tape storage device and a color printer to document the inspection. One pass over a 200m-long bridge generates about 450 Mbytes of radar data and 45 Mbytes of (compressed) video.

The user of the system cannot ride in the trailer while the vehicle is in motion, so an external control computer—a laptop connected to the main computer by local thin-wire ethernet through the trailer front—will be used by the operator in the towing vehicle. While driving over the bridge, the operator can monitor the data acquisition, control certain acquisition and display parameters, and obtain diagnostics. The typical modes of operation are the following:

- Calibration — By driving over rods and plates of known sizes and locations, a set of calibration parameter are set for the scan. This procedure is likely to be needed only infrequently.
- Inspection parameter setup — Before entry on the bridge, the inspection parameters are set up on the main computer (this could be done while parked). Control is transferred to the networked laptop while the trailer is secured and the operator prepares to drive over the bridge.
- Data acquisition — At the start of the bridge, a key-stroke on the laptop initiates the scan. Diagnostics are displayed on the laptop while the main computer is occupied in acquiring and storing the current swath. For multiple passes, this process is restarted once for each pass. High or low speed operation dictates the down-road spatial sampling. A special “bounce diagnostic” tells the operator if the acquired data is, in fact, valid.
- Data analysis — After all data is collected and verified on the laptop, the operator initiates the data processing and display operations. These processes are described in the next section. On the workstation, these operations could take from 30 minutes to an hour to execute, so the operator may wish to stop the vehicle. The data is best viewed on the main computer monitor.
- Diagnostic — In the event of error or missed data, a diagnostic mode of operation allows the user to interrogate the system, locate the problem, and repair it.

3.6. Data processing

Several data processing steps have been identified and are implemented in the computer. The data processing involves conversion of the raw data to a form that is more easily viewed by the operator; i.e., a 3D image. As mentioned above, the signal-to-noise ratio of the radar is sufficient for the bridge-deck application, so it is not the limiting factor in performance; the real issue is removal of clutter. Sources of clutter are surface effects, antenna coupling, motion, calibration errors, jitter, or uninteresting objects in the concrete such as aggregate. Without getting detailed about the steps involved, the general approach for data reduction is as follows:

- Calibration — Apply correction of time and launch point from the previously measured calibration parameters.
- Data preprocessing — Digital bandpass filtering is often applied to the raw radar data.
- Surface reflection — The first surface reflection is measured and removed by alignment and background subtraction.
- Motion compensation — Small amounts of vehicle motion can be detected from radar data and compensated out.
- Tagging to bridge location — A video camera, mounted on the rear of the vehicle a calibrated distance from the array, will collect and tag the bridge location to the radar data. This will allow alignment of multiple passes and the ability to match suspected bridge flaws to known landmarks.
- Image formation — Diffraction tomography using backpropagation [4] is used to form images from the 3D processed radar waveform. Alignment of the various passes happens at this stage.
- Image extraction — Interactively, the operator extracts various 2D images to visualize the bridge deck for flaws.
- Target recognition (future) — Automatic detection and localization of the flaws could aid the user in the inspection process. Farther in the future, we anticipate a way of overlaying previous inspections of the same bridge for comparison purposes.

3.7. Vehicle and packaging

The vehicle used to house the radar array (shown in Figure 1) is a 30-foot-long 8.5-foot-wide trailer specially modified for this first-generation inspection system. This approach is more cost effective than a complete vehicle and is low-maintenance. It has a triple-axle suspension that is smooth enough for the computer and electronics; measurement of acceleration in the unloaded trailer over railroad tracks and other road obstacles at 30 mph yielded less than ±1 g. The floor of the trailer is flat, allowing clear access through the floor for the array and survey wheel. During operation, the two-meter-wide offset-linear array of impulse radar transceivers is suspended roughly 10 cm above the ground while passing over the bridge deck. There are floor cutouts are for two possible arrays, but only one is needed for the current prototype system. The array can also be lifted completely out of its operating position for assembly and maintenance. Shock-mounted electronic racks provide extra vibrational isolation for the computer hardware. Additional features include complete closure for security, vents, air conditioning, AC power generator, external lights and camera mount, survey wheel, and storage compartments.

4. DEPLOYMENT PLANS

Final deployment of the entire HERMES system is scheduled for early 1997. A single-channel system has been used for baseline testing, and an eight-element array (one-eighth of HERMES) is currently undergoing tests. Incorporated into the tests will be a complete calibration suite and diagnostics. We view HERMES as the first prototype development tool that will provide baseline evaluations of a number of bridges. As experience is gained from these measurements, we expect to identify improvements and modifications that will enhance its capabilities. The data collected over time will enable statistical studies on concrete bridges in the United States and open new research areas using the HERMES tool. Follow-on projects in these areas are expected to continue.

In addition to its other capabilities, the HERMES system has been designed to easily incorporate alternate sensors. For example, the FHWA is currently investigating the use of infrared (IR) detectors as another method to detect subsurface flaws. IR cameras can be mounted to the HERMES trailer and the output data fed directly into the internal computer system. This scenario would limit the throughput of the current system, but this problem could be rectified by additional computational resources. We expect long-term development, deployment, and support of similar inspection vehicles to be provided by industry and local departments of transportation.

5. SUMMARY

The HERMES bridge-deck inspection system can image the sub-structure in a two-meter-wide swath of roadway at normal traffic speeds, thus eliminating the need for traffic controls in most cases. The data are stored in real-time and post-processed to reveal 3-cm spatial resolution in the cross-road direction. HERMES was developed out of LLNL expertise in microwave hardware, modeling, and imaging. We expect to field the complete system in winter 1997 and report on statistical results at a later date. Some of the first bridges to be inspected will be ones that are already suspected of having damage and are scheduled for demolition. In this way, we will be able to compare imaging data to the actual road conditions. Analysis of these and other bridge-deck studies by the FHWA will provide valuable feedback for future improvements. Following successful demonstration of the prototype system in the field, we expect to pursue partnerships with commercial entities who can manufacture replicate versions of HERMES for widespread use.

6. ACKNOWLEDGMENTS

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